Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 108 (2007) 123–129
Remote Sensing of Environment
www.elsevier.com/locate/rse

Remotely sensed measurements of forest structure and fuel loads in the Pinelands of New Jersey

Nicholas Skowronski [a], Kenneth Clark [a,*], Ross Nelson [b], John Hom [a], Matt Patterson [a]

[a] *Northern Global Change Program, USDA Forest Service, 11 Campus Blvd., Suite 201, Newtown Square, PA 19073, United States*
[b] *Biospheric Sciences Branch, Building 33, NASA Goddard Space Center, Greenbelt, MD 20771, United States*

Received 22 October 2005; received in revised form 17 August 2006; accepted 9 September 2006

Abstract

We used a single-beam, first return profiling LIDAR (Light Detection and Ranging) measurements of canopy height, intensive biometric measurements in plots, and Forest Inventory and Analysis (FIA) data to quantify forest structure and ladder fuels (defined as vertical fuel continuity between the understory and canopy) in the New Jersey Pinelands. The LIDAR data were recorded at 400 Hz over three intensive areas of 1 km^2 where transects were spaced at 200 m, and along 64 transects spaced 1 km apart (total of ca. 2500 km^2). LIDAR and field measurements of canopy height were similar in the three intensive study areas, with the 80th percentile of LIDAR returns explaining the greatest amount of variability (79%). Correlations between LIDAR data and aboveground tree biomass measured in the field were highly significant when all three 1 km^2 areas were analyzed collectively, with the 80th percentile again explaining the greatest amount of variability (74%). However, when intensive areas were analyzed separately, correlations were poor for Oak/Pine and Pine/Scrub Oak stands. Similar results were obtained using FIA data; at the landscape scale, mean canopy height was positively correlated with aboveground tree biomass, but when forest types were analyzed separately, correlations were significant only for some wetland forests (Pitch Pine lowlands and mixed hardwoods; $r^2=0.74$ and 0.59, respectively), and correlations were poor for upland forests (Oak/Pine, Pine/Oak and Pine/Scrub Oak, $r^2=0.33$, 0.11 and 0.21, respectively). When LIDAR data were binned into 1-m height classes, more LIDAR pulses were recorded from the lowest height classes in stands with greater shrub biomass, and significant differences were detected between stands where recent prescribed fire treatments had been conducted and unburned areas. Our research indicates that single-beam LIDAR can be used for regional-scale (forest biomass) estimates, but that relationships between height and biomass can be poorer at finer scales within individual forest types. Binned data are useful for estimating the presence of ladder fuels (vertical continuity of leaves and branches) and horizontal fuel continuity below the canopy.

Keywords: Single-beam LIDAR; Forest biomass; Ladder fuels; Fuel loads

1. Introduction

LIDAR (Light Detection and Ranging) systems utilize lasers and detectors in various configurations to make accurate measurements of platform to surface distances. LIDAR techniques have been used on a variety of platforms to estimate forest height and canopy structure (e.g., Harding et al., 2001; Lefsky et al., 2002a; Nelson et al., 2003a). Specific applications have been to produce forest carbon inventories (Lefsky et al., 2002b; Nelson et al., 2003b; Patenaude et al., 2004), quantify leaf area and its distribution through the canopy (Parker et al., 2001; Riaño et al., 2004), and estimate structural changes during forest succession (Parker & Russ, 2004). Recently, LIDAR techniques have been used to estimate fuel load parameters for forests (Andersen et al., 2005; Riaño et al., 2003), including understory height, crown bulk density, and crown fuel mass, key parameters used in fire behavior models such as FARSITE and BEHAVEPlus (Andrews et al., 2003; Finney, 2004).

LIDAR represents an important tool for wildfire managers in forested regions. However, one of the problems in using more complex LIDAR products (i.e., scanning LIDAR) and their platforms is that they are expensive and beyond the scope of most wildfire management agencies. Our objective was to use a relatively simple LIDAR system constructed from “off the

* Corresponding author. USDA Forest Service, P.O. Box 232, New Lisbon, NJ 08064, United States. Tel.: +1 609 894 0325.
E-mail address: kennethclark@fs.fed.us (K. Clark).

0034-4257/$ - see front matter © 2007 Published by Elsevier Inc.
doi:10.1016/j.rse.2006.09.032

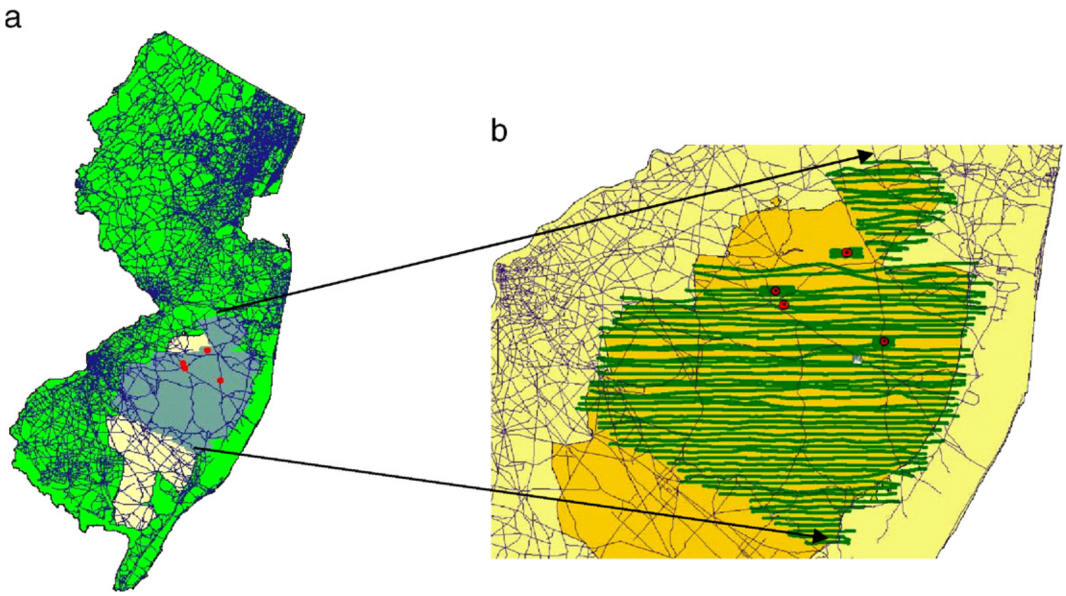

Fig. 1. The Pinelands of New Jersey (blue) and intensive study areas (red dots). LIDAR flight lines were spaced at 1 km over the Pinelands and at 200 m over the intensive study areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shelf" components which can be flown on a platform that would be available to many fire managers to estimate two key fuel loading parameters, total tree biomass and the presence of ladder fuels. We define "ladder fuels" as fuel consisting of foliage and branches that produce vertical continuity between the understory and the canopy. Ladder fuels are important for fire behavior because they facilitate the transition of surface fires to the canopy, where they are much more difficult and expensive to suppress. We used forest census data that is available locally and on the internet (Forest Inventory and Analysis data; http://fia.fs.fed.us). Specifically, we used single-beam, first return profiling LIDAR measurements made by a helicopter owned by the New Jersey Forest Fire Service (NJFFS), intensive biometric measurements made on 1 km^2 grids, and Forest Inventory and Analysis (FIA) data to characterize forest structure and ladder fuels in the New Jersey Pinelands.

2. Study area

Study sites are located in Burlington and Ocean Counties in southern New Jersey. The Pinelands encompass 1.1 million acres of pine, oak and wetland forests, covering 23% of New Jersey (Fig. 1). The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 °C in January and June, respectively (1930–2004; NJ State Climatologist). Mean annual precipitation is 1123 ± 182 mm. The terrain consists of plains, low-angle slopes and wetlands, with a maximum elevation of 62.5 m. Soils are derived from the Cohansey and Kirkwood Formations (Lakewood and Sassafras soils), and are coarse-textured, sandy, acidic, and have extremely low cation exchange capacity and nutrient status (Tedrow, 1986). Despite the widespread occurrence of sandy, well-drained, nutrient-poor soils, upland forests are moderately productive and fuels accumulate rapidly (Pan et al., 2006).

Upland forests comprise 62% of forested lands in the Pinelands, and are dominated by three major communities; oak dominated forests with scattered pines (Oak/Pine), pine dominated forests with oaks in the overstory (Pine/Oak), and Pitch Pine dominated forests with Scrub Oaks and shrubs in the understory (Pine/Scrub Oak) (Lathrop & Kaplan, 2004; McCormick & Jones, 1973; Table 1). All upland forests have moderate to dense shrub cover in the understory, primarily *Vaccinium* spp., *Galussacia* spp., *Kalmia* spp. and *Quercus* spp., and sedges, mosses and lichens are also present. Upland forests are of major concern to fire managers, because dense residential developments and key transportation corridors occur adjacent to these flammable forests.

3. LIDAR measurements

LIDAR data were collected in mid-April, 2004 during leaf-off conditions for deciduous species. Sixty-four east/west flight lines spaced 1 km apart (total of ca. 2500 km^2) were generated using a GIS database, and then flight line coordinates were downloaded to the onboard GPS system on a Bell Jet Ranger

Table 1
Major forest types in the Pinelands of New Jersey and their extent (adapted from Lathrop & Kaplan, 2004)

Forest type	% of landscape	Area (km^2)
Upland forests		
Oak/Pine	19.1	725.5
Pine/Oak	13.1	497.0
Pitch Pine/Scrub Oak	9.6	365.3
Wetland forests		
Pitch Pine lowland	12.3	468.1
Mixed hardwood/conifer	8.6	326.0
Hardwood swamp	6.0	228.1
Atlantic White Cedar swamp	1.4	53.0

Table 2
Structural characteristics of three 1 km^2 intensive study plots in the Pinelands of New Jersey

	Oak/Pine	Pine/Oak	Pine/Scrub Oak
Overstory			
Canopy height (m)	13.5±1.2	10.5±1.9	8.7±0.9
Basal area (m^2 ha^{-1})	15.7±3.8	11.5±5.2	9.7±3.7
Tree biomass (t ha^{-1})	83.1±21.5	47.6±25.5	32.7±16.7
Understory			
Scrub Oak biomass (t ha^{-2})	0.2±0.5	2.2±2.1	0.7±0.7
Shrub biomass (t ha^{-2})	1.7±1.1	1.1±1.0	3.2±0.8
Total biomass (t ha^{-2})	1.9±1.1	3.3±2.1	3.9±1.3

Values are means±1 SD.

helicopter operated by the NJFFS. Additional flight lines spaced 200 m apart were generated for three 1 km^2 intensive sampling areas surrounding existing fire weather towers. We attempted to fly over the center of each forest census plot (see below) in the three intensive areas. Fig. 1 illustrates the location of the Pinelands and the LIDAR flight lines.

LIDAR measurements were made using the portable airborne laser system (PALS) described in detail by Nelson et al. (2003a). The helicopter flew at 100 m height at ca. 50 m s^{-1}. The laser pulse frequency of 2000 Hz was subsampled at 400 Hz, thus LIDAR returns were spaced ca. 0.125 m apart. LIDAR returns were integrated with dGPS signals providing a position estimate with 5–7 m accuracy approximately every 100 m. Data were recorded on a laptop computer running LabVIEW data acquisition software (National Instruments Corp., Austin, Texas). A ground line was extrapolated from unvegetated surfaces (roads, water, etc.) at approximately 100 m intervals. Using the maximum platform to surface distances obtained, the shape of the ground surface was estimated by cubic spline interpolation (Nelson et al., 2003a). Each LIDAR return was classified using a 2001 New Jersey land cover map generated from Landsat images in a GIS database (Table 1; Lathrop & Kaplan, 2004). LIDAR returns then were grouped into 80 m segments for each forest type to approximate the diameter of a circle that would encompass four FIA-type sub-plots sampled in the field (see below).

LIDAR data were analyzed as the arithmetic and quadratic mean of all returns, the average and quadratic means of all

Table 3
Summary statistics for LIDAR measurements at three 1 km^2 intensive study sites in the Pinelands of New Jersey

	Oak/Pine	Pine/Oak	Pine/Scrub Oak
Height (m)	7.9±1.6	5.0±1.6	3.9±1.2
Quadratic height (m)	9.6±1.6	6.3±1.7	5.1±1.3
Canopy height (m)[a]	11.1±1.6	7.8±1.8	6.7±1.2
Quadratic canopy ht (m)[a]	11.4±1.6	8.0±1.9	7.0±1.3
80th percentile	12.9±1.9	8.8±2.3	6.9±1.6
90th percentile	14.2±1.9	9.7±2.4	8.5±2.1
All returns >3 m ht (%)	69.7±9.3	60.5±12.6	51.2±13.0
All returns >4 m ht (%)	68.1±9.1	56.3±13.3	46.0±15.0

Values are means±1 SD.
[a] Indicates all LIDAR returns above 4 m height.

Table 4
Relationships between plot based measurements (mean canopy height, m) and LIDAR measurements along 80-m segments flown directly over center plots (various metrics)

LIDAR measurement	Equation	r^2	*P* value
Mean canopy height			
All heights	$y=0.741x-2.45$	0.632	<0.01
Quadratic mean height	$y=0.859x-2.331$	0.717	<0.01
Mean canopy height[a]	$y=0.871x-0.925$	0.743	<0.01
Quadratic canopy ht[a]	$y=0.898x-0.909$	0.748	<0.01
80th percentile	$y=1.178x-3.237$	0.791	<0.01
90th percentile	$y=1.151x-1.673$	0.723	<0.01
Basal area			
Returns >3 m ht	$y=1.501x+45.546$	0.201	NS
Returns >4 m ht	$y=2.196x+34.758$	0.347	<0.05

Data from the 1 km^2 Oak/Pine, Pine/Oak, and Pine/Scrub Oak stands are pooled.
[a] Indicates all LIDAR returns above 4 m height.

returns >3 m and >4 m heights, and as percentiles (90%, 80%, 70%, etc.) of the highest elevations along each segment for each forest type. Additionally, LIDAR returns obtained over the three 1 km^2 intensive areas and over pairs of recent prescribed fires and unburned areas were binned into 1 m height classes by normalizing returns for each bin:

$$\text{Percentage of returns in the 1st height bin } n = (R_n/R_{\text{total}})*100$$

$$\text{Percentage of returns in the 2nd height bin } n+1 = (R_{n+1}/(R_{\text{total}}-R_n))*100$$

Where R_n=the number of returns from the upper 1 m of the canopy, R_{total} is the total number of returns along the segment,

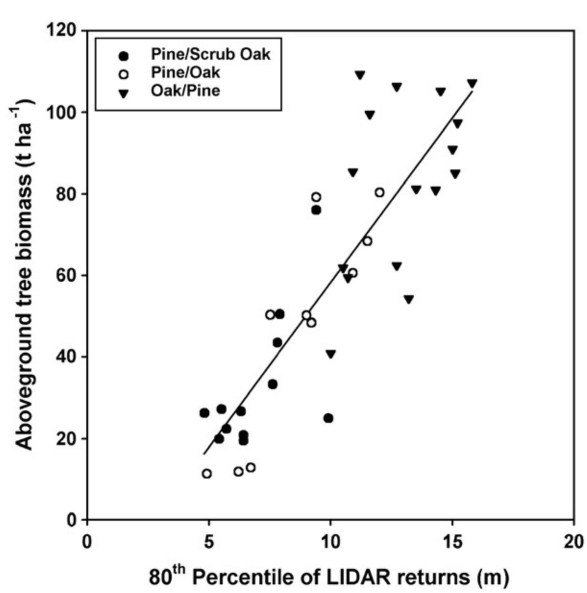

Fig. 2. The relationship between stand biomass and 80th percentile of LIDAR measurements (shortest 20% of all platform to canopy returns) for the three 1 km^2 intensive study areas.

Table 5
Relationships between LIDAR 80th percentile height and overstory biomass (t ha^{-2}) for the three 1 km^2 sites collectively (Fig. 1, $n=36$) or separately ($n=12$ plots for each site)

Attribute	Equation	r^2	P value
All plots	$y=6.022x$	0.687	<0.01
Oak/Pine	$y=6.404x$	0.228	NS
Pine/Oak	$y=5.684x$	0.636	<0.01
Pine/Scrub Oak	$y=4.795x$	0.355	NS

Equations were forced through zero.

and R_{n+1} is the number of returns from the next lower 1 m layer of the canopy. We analyzed data from bins 1–2 m, 2–3 m, and 3–4 m heights for the presence of ladder fuels, because bin 0–1 m proved unusable due to noise generated from creation of the reference ground spline.

4. Field-based forest structure measurements

We selected three sites for intensive study, an Oak/Pine stand at the Silas Little Experimental Forest, a Pine/Oak stand at Fort Dix Army Base, and a Pine/Scrub Oak stand at Cedar Bridge fire tower (Fig. 1, Table 2). Each site has an existing fire weather/eddy flux tower, and a 1 km^2 grid was superimposed on each tower and 16 points were generated at regular intervals in a 4×4 arrangement. Points were used to locate centers of FIA-type plots (four 168 m^2 sub-plots, one in the center and the others located 36.6 m from the center point at 120, 240 and 360°; FIA sampling protocols described at http://fia.fs.fed.us). Tree species, height, diameter at 1.37 m (DBH), crown position, and tree condition were measured in each plot. Data from the four sub-plots were averaged, and basal area and biomass were calculated on a per ha basis. Allometric equations were used to calculate tree biomass in each plot (Whittaker & Woodwell, 1968). Shrub biomass was harvested in 20 1 m^2 sub-plots located near each tower. We compared mean tree height averaged for all four sub-plots to LIDAR measurements of canopy height, and basal area averaged for all four sub-plots to the number of LIDAR returns >3 m and >4 m. Correlation analyses were used to determine significance levels for relationships between field and LIDAR measurements (Sokal & Rohlf, 1995).

Table 6
The relationship between canopy height and tree biomass for major forest types in Burlington and Ocean Cos., southern New Jersey

Forest type	Equation	r^2	n	P value
All FIA	$y=6.04x$	0.56	74	<0.01
Upland forests				
Oak/Pine	$y=5.57x$	0.328	14	NS
Pine/Oak	$y=5.36x$	0.107	8	NS
Pitch Pine/Scrub Oak	$y=5.19x$	0.211	26	NS
Wetland forests				
Pitch Pine lowlands	$y=6.34x$	0.739	9	<0.01
Mixed hardwoods	$y=6.32x$	0.590	10	<0.05
Atlantic White Cedar	$y=7.92x$	0.430	7	NS

Units are meters for canopy height and metric tons ha^{-1} for biomass. Equations were forced through zero. "All FIA" is all forest types pooled.

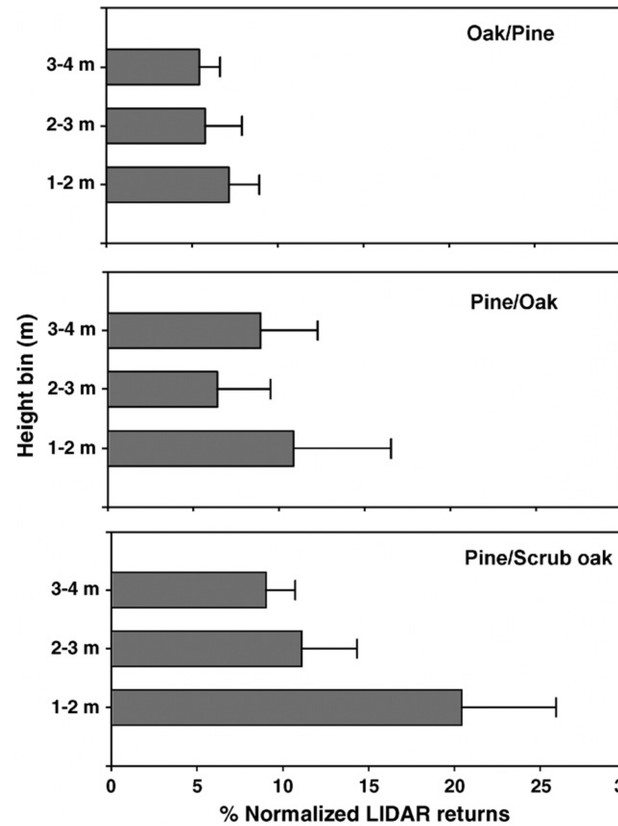

Fig. 3. Understory biomass and vegetation cover estimated from LIDAR measurements at the three 1 km^2 intensive areas. LIDAR data are binned in 1 m increments, ±1 SD. Bins 1–2 m, 2–3 m and 3–4 m are shown.

FIA data for the Pinelands were obtained for Burlington and Ocean Counties (the two counties that were flown with LIDAR) on the internet (http://fia.fs.fed.us). Plots were censused in 1999, and we obtained data for 74 sites where all four sub-plots were forested. We grouped FIA data by forest type, and used them to further explore the relationships between mean tree

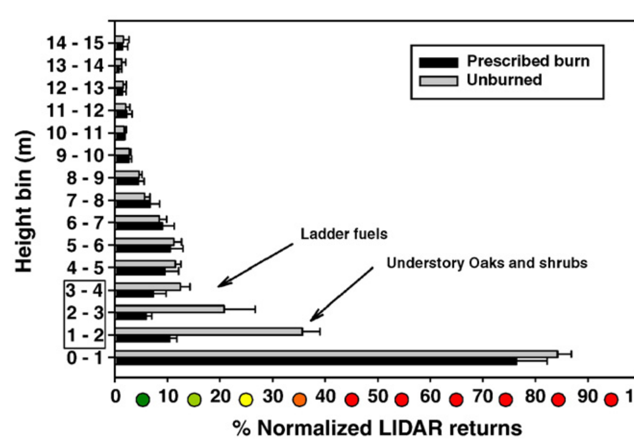

Fig. 4. Percent vegetation cover and vegetation height estimated from LIDAR measurements near Cedar Bridge fire tower. The recently burned area was the site of a prescribed fire 2 months previously, and the unburned site has not burned since 1995. Data are binned in 1 m increments, ±1 SD. Differences between normalized percentage of LIDAR returns are significant for 1–2 m and 2–3 m height class bins at $P<0.05$.

Table 7
Structural characteristics for prescribed fire treatment and unburned area shown in Fig. 4, measured using fuel photoseries protocols (Wright et al., 2007)

Attribute	Treated	Unburned	*T*	*P* value
Overstory				
Cover (%)	50.0±8.3	51.0±7.4	1.59	NS
Height (m)	6.4±2.8	5.5±2.5	2.47	<0.01
DBH (cm)	12.0±6.7	8.7±5.7	5.91	<0.001
Understory				
Sapling cover (%)	0.0±0.0	21.9±13.7	37.33	<0.001
Seedling cover (%)	16.6±1.9	15.6±2.8	2.91	<0.01
Shrub cover (%)	36.5±4.9	72.0±14.4	50.98	<0.001
Sapling height (m)	1.3±0.7	1.7±0.1	2.82	<0.05
Seedling height (m)	1.0±0.1	1.1±0.1	1.41	NS
Shrub height (m)	0.5±0.4	0.7±0.1	1.78	NS
Shrub biomass (t ha^{-1})	0.85±0.75	3.29±1.20	109.98	<0.001

A prescribed fire was conducted two months previous to the collection of LIDAR data.

height and stand biomass and allometry. Correlation analyses were used to determine significance levels for each relationship.

Forest structure data were collected from two additional sites located near the Cedar Bridge fire tower, following protocols detailed in Wright et al. (2007). Plots measured 583.7 m^2, and tree height and DBH, and crown cover were measured in each plot. Seedling, sapling, and shrub cover and biomass were sampled in six to ten sub-plots measuring 1 m^2 and 4 m^2 at regular locations within the large plot at each site. These data were compared to the height binned LIDAR data.

5. Results

5.1. LIDAR vs. field measurements

Mean canopy heights measured in the field in the three 1 km^2 intensive areas were best approximated using the 80th percentile of all LIDAR returns, which represents the shortest 20% of platform to canopy distances along each 80 m segment, or the 90th percentile of all LIDAR returns (Tables 2 and 3). When data from all three intensive areas were pooled, all LIDAR height metrics were significantly related to mean canopy height measured in the field, but the 80th percentile value explained the greatest amount of variability in mean canopy height (Table 4). Percent of all LIDAR returns >3 m or >4 m height were only weak predictors of plot basal area (Table 4). The 80th percentile values also explained the greatest variation in tree biomass when plots were pooled, although a number of the other metrics had similar, significant r^2 values (Fig. 2). However, when the three stands were considered separately, both the Oak/Pine and Pine Scrub Oak sites had insignificant relationships between 80th percentile values of LIDAR returns and tree biomass in plots (Table 5).

5.2. FIA data

Using FIA data from Ocean and Burlington Counties, mean canopy height measured in the field was positively correlated with aboveground tree biomass when data from all forest types were pooled (Table 6). However, similar to the relationships between LIDAR measurements and tree biomass in the 1 km^2 intensive areas, correlations between mean tree height and biomass were only significant for some forests (Pitch Pine lowlands and mixed hardwoods) when forest types were considered separately. Correlations between mean tree height and biomass were weakest for upland forests with >50% Pine cover (Pine/Oak and Pine/Scrub oak; Table 5). These forest types also had the poorest relationship between mean tree height and basal area (r^2=0.09 and 0.43 for Pine/Oak and Pine/Scrub Oak, respectively; mean r^2 for all other forest types is 0.51).

5.3. LIDAR measurements and ladder fuels

When data from upland forests were binned into 1-m height classes, differences in the lower height classes were detected among the 1 km^2 intensive stands (Fig. 3). A greater number of

Fig. 5. A section of a fuel loading map produced for the New Jersey Forest Fire Service using LIDAR data. Binned data were used to estimate understory cover in the 1–4 m height class. Crosshatching indicates a prescribed fire, conducted 3 months previous to LIDAR flights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

LIDAR returns from the lowest height classes corresponded to greater understory biomass at the Pine/Oak and Pine/Scrub Oak intensive sites compared with the Oak/Pine site (Table 2, Fig. 3). Differences between stands where recent fuel reduction treatments were conducted 2 to 3 months prior to the LIDAR flights and unburned areas were detected in the lowest height classes (bins 1–2 m and 2–3 m heights, $P < 0.05$, Fig. 4). A greater number of LIDAR returns corresponded to greater cover of saplings and shrubs in the understory, and to greater shrub biomass at the unburned site (Table 7). LIDAR data thus indicates both vertical fuel structure (percentage of LIDAR returns in height classes 1–2 m, 2–3 m, and 3–4 m) and horizontal fuel continuity (percentage of returns ± SD within a height class). These fuel characteristics are key to wildfire behavior, and largely control the transition of ground fires to the canopy, and facilitate the spread of surface fires. In both of these analyses, bin 0–1 m proved unusable because of noise generated from creation of the reference ground spline.

An example of maps of the occurrence of ladder fuels derived from LIDAR measurements that we produce for the NJFFS is shown in Fig. 5. Green dots indicate the lowest cover value of shrubs and Scrub Oaks in the understory along an 80-m segment (representing 0–10% of normalized LIDAR returns at 1–4 m height), while red dots indicate the greatest cover value (representing 40.1–100% of normalized LIDAR returns at 1–4 m height).

6. Discussion

LIDAR data have been used successfully to estimate forest canopy structure and biomass in a wide range of forest ecosystems (e.g., Lefsky et al., 2002b; Nelson et al., 2003b; Parker & Russ, 2004). In these studies, LIDAR measurements of mean canopy height are strongly related to stand biomass, with correlation coefficients typically ranging from 0.6 to 0.8. However, significant correlations are dependent upon a strong relationship between canopy height and stand basal area. We found that when all three 1 km^2 intensive areas or the regional-scale FIA data were analyzed, the relationship between mean canopy height and biomass was significant, but at the low end of the range reported by other authors. It is notable that the range of mean canopy heights is relatively wide in our combined analyses (7.1 to 16.0 m for the three 1 km^2 intensive areas, and 6.2 to 21.3 m for the 74 FIA plots). However, when either the 1 km^2 intensive areas or individual upland forest types using FIA data are considered separately, the relationship between canopy height and biomass was often weak. Further analysis using the 1 km^2 intensive plots indicates that tree height is asymptotic with respect to DBH, because the relationship between height and DBH for the dominant species was best modeled as a logarithmic relationship (Pitch Pine; ht = 6.144 ln (DBH) − 5.061, $r^2 = 0.74$, Chestnut Oak; ht = 5.970 ln (DBH) − 2.515, $r^2 = 0.81$, Black Oak; ht = 5.970 ln (DBH) − 2.515, $r^2 = 0.76$). Thus, where the relationship between tree height and basal area is weak, it is difficult to estimate stand biomass accurately using LIDAR data. In addition to these allometric relations of trees, both wildfires and harvest activities have altered the structure of upland forest stands in the Pinelands. For example, within our 1 km^2 intensive plots, sub-plots where thinning treatments had occurred showed the poorest relationship between canopy height and biomass.

Despite methodological limitations, LIDAR measurements are useful for determining carbon storage and leaf area distribution in forests. However, total biomass inventories are not as essential to fire managers as are accurate estimates of the mass and distribution of live and dead fuels (Andersen et al., 2005; Riaño et al., 2003). Our results indicate that relatively simple single-beam LIDAR data can provide useful information to fire managers. Although the relationships between canopy height and understory biomass, or canopy height and fuels on the forest floor are often poor, aggregating data into height bins produces key information on the distribution of live fuels in the understory and sub-canopy. In our examples, an increase in the number of LIDAR returns from the 1–2 m and 2–3 m height classes correspond to greater shrub biomass in the understory. This is perhaps the greatest benefit of single-beam LIDAR data to fire managers, because these data can be used to detect the vertical continuity of fuels, termed ladder fuels. Ladder fuels largely determine the rate of transition of wildfires from ground to canopy, where fires are much more difficult and expensive to control.

A number of methods have been employed to analyze LIDAR metrics, including maximum heights along a transect, mean heights (arithmetic, geometric), and quartile-based metrics, such as used here. Interestingly, the 80th quartile has been shown to be the best predictor of biomass in other structurally complex forests ($r = 0.74$; Patenaude et al., 2004).

Binning data is relatively straight forward and computationally simple. Other data processing methods, such as spectral analyses could also be employed to examine LIDAR pulse densities. Similar approaches have been used successfully in other studies, for example, cluster analysis has been used to determine crown base height, and thus tree and understory heights for estimating fuel loads (Riaño et al., 2003).

LIDAR measurements can be used to produce an additional GIS layer in fuel loading maps, and can then be used by fire managers to determine the locations of dense fuel accumulations near wildland urban interface, and to prioritize fuel reduction treatments. The map shown in Fig. 5 is a sample of the ladder fuels map that was superimposed upon a number of other GIS layers, including the forest classification layer and the prescribed fire maps for 2004. We can produce these maps on an operational basis, and they have been used by the NJFFS to plan and prioritize prescribed fire treatments. Our data indicates that LIDAR measurements can also be used to evaluate the effectiveness of fuel reduction treatments rapidly and inexpensively.

7. Conclusions

LIDAR data are useful for estimating forest structure and biomass in many forests, but where a poor relationship exists between tree height and basal area, biomass estimates may be less accurate. Forest census data indicates that tree height is asymptotic with respect to DBH at relatively short heights in upland forests in the Pinelands, and previous management and wildfires that substantially alter stand basal area also introduce large variations in height to biomass relationships. Binning data into height size classes can be used to detect "ladder fuels", and when overlain on other GIS layers, can be used to prioritize and evaluate fuel reduction treatments.

Acknowledgements

This research is funded by the Eastern Landfire Prototype and the National Fire Plan to develop fuel loading and fuel structure maps, and to assist the NJFFS and other wildfire management agencies to prioritize fuel reduction treatments.

References

Andersen, H. -E., McGaughey, R. J., & Reutebuch, S. E. (2005). Estimating forest canopy fuel parameters using LIDAR data. *Remote Sensing of Environment*, *94*, 441−449.

Andrews, P. L., Bevins, C. D., & Seli, R. C. (2003). BehavePlus fire modeling system, version 2.0: User's guide gen. tech. rep. RMRS-GTR-106WWW Ogden, UT: Department of Agriculture, Forest Service, Rocky Mountain Research Station. 132 pp.

Finney, M. A. (2004). FARSITE: Fire area simulator-model development and evaluation res. pap. RMRS-RP-4 revised Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 pp.

Harding, D. J., Lefsky, M. A., Parker, G. G., & Blair, B. (2001). Laser altimetry canopy height profiles: Methods and validation for closed-canopy, broad-leaved forests. *Remote Sensing of Environment*, *76*, 283−297.

Lathrop, R., & Kaplan, M. B. (2004). New Jersey land use/land cover update: 2000–2001 : New Jersey Department of Environmental Protection. 35 pp.

Lefsky, M. A., Cohen, W. B., Harding, D. J., Parker, G. G., Acker, S. A., & Gower, S. T. (2002). Lidar remote sensing of aboveground biomass in three biomes. *Global Ecology and Biogeography*, *11*, 393−400.

Lefsky, M. A., Cohen, W. B., Parker, G. G., & Harding, D. J. (2002). LIDAR remote sensing for ecosystem studies. *Bioscience*, *52*, 19−30.

McCormick, J., & Jones, L. (1973). *The Pine barrens: Vegetation geography. Research Report*, *Vol. 3*: New Jersey State Museum. 76 pp.

Nelson, R., Parker, G. G., & Horn, M. (2003). A portable airborne laser system for forest inventory. *Photogrammetric Engineering and Remote Sensing*, *69*, 267−273.

Nelson, R., Valenti, M. A., Short, A., & Keller, C. (2003). A multiple resource inventory of Delaware using airborne laser data. *Bioscience*, *35*, 981−992.

Pan, Y., Birdsey, R., Hom, J., McCullough, K., & Clark, K. (2006). Improved estimates of net primary productivity from MODIS satellite data at regional and local scales. *Ecological Applications*, *16*, 125−132.

Parker, G. G., Lefsky, M. A., & Harding, D. J. (2001). PAR transmittance in forest canopies determined from airborne lidar altimetry and from in-canopy quantum measurements. *Remote Sensing of Environment*, *76*, 298−309.

Parker, G. G., & Russ, M. E. (2004). The canopy surface and stand development: Assessing forest canopy structure and complexity with near-surface altimetry. *Forest Ecology and Management*, *189*, 307−315.

Patenaude, G., Hill, R. A., Milne, R., Gaveau, D. L. A., Briggs, B. B. J., & Dawson, T. P. (2004). Quantifying forest above ground carbon content using LIDAR remote sensing. *Remote Sensing of Environment*, *76*, 298−309.

Riaño, D., Chuvieco, E., Condes, S., Gonzalez-Matesanz, J., & Ustin, S. L. (2004). Generation of crown bulk density for *Pinus sylvestris* L. from lidar. *Remote Sensing of Environment*, *92*, 345−352.

Riaño, D., Meier, E., Allgower, B., Chuvieco, E., & Ustin, S. L. (2003). Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. *Remote Sensing of Environment*, *86*, 177−186.

Sokal, R. R., & Rohlf, F. J. (1995). Biometry San Francisco, California, USA: W.H. Freeman.

Tedrow, J. C. F. (1986). Soils of New Jersey. New Jersey agricultural experiment station publication A-15134–1-82 Malabar, FL: Krieger Publishing Co.

Whittaker, R. H., & Woodwell, G. M. (1968). Dimension and production relations of trees and shrubs in the Brookhaven forest, New York. *Journal of Ecology*, *57*, 1−25.

Wright, C. S., Ottmar, R. D., & Vihnanek, R. E. (2007). Stereo photo series for quantifying natural fuels. Volume VIII: Hardwood, Pitch Pine, and Red Spruce/Balsam Fir types in the Northeastern United States. PMS 840 Boise, ID: NationalWildfire Coordinating Group, National Interagency Fire Center 91 pp.